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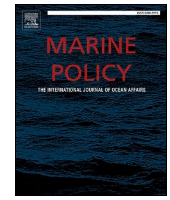


# Enhancing science-policy interface in marine environmental governance: Oil spill response models as boundary objects in the Gulf of Finland, Baltic Sea

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A B S T R A C T

Scientific models provide important input to the governance of complex socio-ecological risks. However, scientific knowledge rarely translates to policy in a simple, direct manner. By focusing on the use of scientific models for oil spill risk assessment and management in the Gulf of Finland (GoF), Baltic Sea, this paper aims to enhance the understanding of the capacity of scientific models to connect science, operational decision-making, and policy. In this study, we conceptualize scientific models as boundary objects, i.e. tools that facilitate interactions between different actors, types of knowledge, and perspectives across system boundaries. The study focuses on the different affordances associated with the models regarding their ability to represent, share, and convey knowledge between science and policy and to link the involved knowledge to action (i.e. changes in practice and in policy). We explore 1) how do the different oil spill models work as boundary objects in the science-policy interface, 2) how do different science-policy contexts affect the model affordances, and vice versa. We also provide recommendations for future research. The study is based on interviews of modelers/researchers, response operators, and policymakers. The results suggest that the existing models lack several of the important affordances that are required to successfully integrate different types of knowledge and transform new knowledge to action. As such, we suggest that currently models remain as instrumental, calculative, tools that support pre-determined policies rather than as means for exploring alternative framings of risks and the possible solutions. Finally, we argue that the co-production of knowledge best supports the plurality of model affordances needed to enable transformative change in policy and practice.

## 1. Introduction

Governing complex socio-ecological problems requires an adaptive approach and decision-making informed by science [1,2,93]. Despite the heightened role of science, a pervasive gap, however, exists between the knowledge producers (often scientists) and knowledge users (e.g. practitioners, policymakers, and other extra-scientific stakeholders) as the integration of scientific knowledge into environmental decision-making processes is challenging and rarely straightforward [2–4].

A growing body of research focuses on the questions relating to the production of knowledge for policy making, and the interaction between science and policy [1,3–11]. Much of the literature, however, focuses on rather simple and linear ideas about how research can be utilized to support policymaking [6]. As policy processes are complicated, unpredictable, and include uncertainty and a diversity of values [3,4,8,10], it is crucial to gain a better understanding of the "supply" of knowledge, the "demand" for science, as well as the complex and dynamic

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relationship between the two [9].

Scientific models provide both researchers and end-users, e.g. practitioners and policymakers, with new insight and deeper understanding of environmental phenomena, while also supporting management and policymaking [1,12,13]. Models are often considered as static, instrumental, tools that provide technical solutions to specific pre-determined problems in a linear manner, i.e. where knowledge produced by scientists (e.g. on the ecological impacts of potential oil spill) is considered to translate to changes in practice and in policy (e.g. changes in oil spill response / risk management) in a direct, simple, manner. In the governance of complex socio-ecological risks, however, the role of models and modelling has begun to shift from the merely instrumental, calculative one to that of facilitating interactions between different actors, types of knowledge, perspectives, and dependencies across system boundaries. Franco [14,15].

Models can be conceptualized as boundary objects, which refers to a theoretical concept that is often described as a tool for integrating different types of knowledge and linking knowledge to action [16]. The capacity of boundary objects to do so depend on the affordances, i.e. the possibilities for action, associated with the object [15,17–19]. The affordances are shaped by the context through which the models are produced, i.e. social and policy processes influence the potential of models to act as boundary objects [19].

By focusing on the use of scientific models as boundary objects in oil spill risk governance in the Gulf of Finland (GoF), Baltic Sea, this paper aims to enhance the understanding of the capacity of scientific models to connect science, operational decision-making, and policy. Tanker traffic in the GoF has grown significantly since the early 2000s and in the case of a large-scale oil spill, the environmental, social, andeconomic impacts could be disastrous. Oil spill risks can be described as complex risks, characterized by high levels of uncertainty as well as ambiguity, i.e. values, risk interpretations and perceptions, and framings of individuals [20,21]. Scientific models have gained a central role in the assessment, management and governance of oil spill risks in the GoF. Our study focuses on the use of pollution preparedness and response (PPR) models, i.e. models that analyze the occurrence of oil spills, the effectiveness of oil spill response, and the environmental, social, andeconomic impacts of oil spills. The models include both operational models that are deterministic (models that provide point estimates) and Bayesian network models (BN models; probabilistic models that treat uncertainty explicitly) that have been developed to gain further understanding of oil spill risks in order to aid decision making and risk assessment and management.

We analyze the potential of oil spill models to act as boundary objects in the science-policy interface related to the management of oil spill risks in the GoF, and connected challenges. The study focuses on the different affordances associated with the models, regarding their ability to represent, share, and convey knowledge between science and policy, and to link the involved knowledge to action. Through this analysis, we seek answers to the following research questions: 1) how do the different oil spill models work as boundary objects in the science-policy interface, and 2) how do different science-policy contexts affect the model affordances, and vice versa. Finally, we provide recommendations for future research based on the key knowledge needs as identified by the interviewees. The study is based on interviews of modelers/researchers, response operators, and policymakers.

The paper is structured as follows. The Gulf of Finland case study is introduced in Section 2. Section 3 provides a theoretical framework for the study and describes the methods. In Section 4, we examine the potential of the different models to act as boundary objects by exploring their affordances. In Section 5, we analyze how different science-policy contexts can either limit or enable the affordances of the models and what type of contexts best support the capacity of models to act as boundary objects. The concluding remarks are provided in Section 6.

## 2. Case study

### 2.1. Oil spill risks in the GoF

Maritime traffic has increased rapidly in a short period of time in the Baltic Sea, and especially so in the GoF [22,23]. The increase is mainly due to the construction and development of Russian ports, such as Primorsk and Ust-Luga, in the 2000s. Today, approximately half of all Russian oil is transported via the Gulf of Finland [23]. The largest tankers in the GoF can carry over 150,000 tons of oil [22,23]. While the increase in tanker traffic has halted in the recent years, maritime cargo and passenger traffic is still growing in the GoF [23]. The risk of a large-scale oil spill accident is, therefore, considered as significant [24]. The risk can be further heightened in the cases of, e.g. severe weather conditions (storms and winter conditions when the sea is covered by ice), faults in passage planning, and/ or when transferring cargo or cargo oil [23]. Further, the predicted growth in automated traffic could increase the risk of an oil spill [23,25]. (Fig. 1).

The increased maritime traffic poses a threat to the sensitive marine and coastal ecosystems. The Baltic Sea is a unique ecosystem with globally exceptional features, such as, low salinity, shallow waters, vast archipelago, regular ice cover, and poor water exchange (see e.g. [27]). The biota is a mixture of marine and freshwater species that have adapted to survive in the low salinity conditions. The Baltic Sea is also an important migratory route for many Arctic birds ([27]). The ecosystem effects of a large-scale oil spill could be long-lasting and especially endangered species would be in danger [28–30]. Further, as the area is already affected by multiple human-induced stressors including, e.g. eutrophication, invasive species, and increasingly also the effects of climate change, the impacts of a potential oil spill could be fatal to many of the Baltic Sea species and habitats. A large-scale oil spill could also have significant (short and/or long-term) economic [31–36], and social as well as-cultural [37,38] consequences as exemplified by previous large-scale oil spills, such as the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska; the 1999 Erika oil spill in Brittany; the 2002 Prestige oil spill in Spain and Portugal, and; the 2010 BP Deepwater Horizon oil spill in the Gulf of Mexico.

### 2.2. Governance and management of oil spill risks in the Gulf of Finland

The oil spill risk governance framework includes both preventive and responsive measures. Preventive measures in the GoF include, e.g. Vessel Traffic Services (VTS; [39]) and the Mandatory Ship Reporting System (GOFREP; [40]). Finland, Estonia and Russia maintain VTS along their respective coastlines in the GoF, as well as GOFREP that covers the international waters. However, in the case of an oil spill, effective response is important. The regulatory framework for environmental response operations in the GoF is based on various international conventions, as well as regional and national co-operation [41].

The International Convention for the Prevention of Pollution from Ships (MARPOL, adopted in 1973 and 1978 respectively [86]) covers prevention of pollution of the marine environment by ships from operational or accidental causes. Under the International Maritime Organization (IMO) International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC convention, adopted in 1990 [87]), all parties are required to establish measures for dealing with pollution incidents, either nationally or in co-operation with other countries. Due to its environmental features and the vulnerability to damage by international maritime activities, IMO has designated the Baltic Sea as a Particularly Sensitive Sea Area (PSSA), i.e. an area that needs special protection through the action by the IMO. Finland is also part of both the International Oil Pollution Compensation Fund (the 1992 International Convention on Civil Liability for Oil Pollution Damage [88] and the 1992 International Fund for Compensation of Oil Pollution [89]) and the supplementary fund (the 2003 Supplementary Fund Protocol [90]), which provides financial compensation for damages in the case of oil

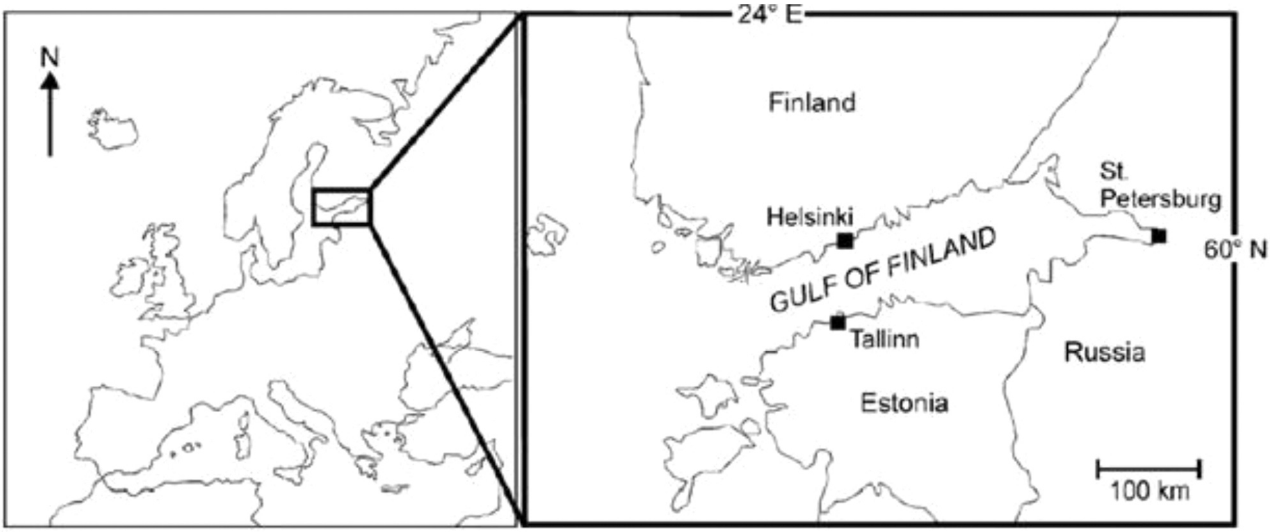


**Fig. 1.** The location of Gulf of Finland.
(Adopted from [26]).

tanker spills.

Cooperation in the Baltic Sea is based on the Convention on the Protection of the Marine Environment of the Baltic Sea Area (the 1992 Helsinki Convention). In accordance with the convention, all states are to maintain ability to respond to oil spills in the marine environment of the Baltic Sea area. Nordic cooperation is based on the Agreement concerning Cooperation in Taking Measures against Pollution of the Sea by Oil or other Harmful Substances (the Copenhagen Agreement). In addition, Finland has bilateral agreements on oil pollution response with Russia (1989) and Estonia (1995). At a European level, the European Maritime Safety Agency (EMSA) can provide response equipment for joint use and by renting response vessels. Joint oil spill response exercises are held regularly under, e.g. the Helsinki Convention and the Copenhagen agreement.

In Finland, the Finnish Border Guard, under the Ministry of the Interior, is responsible for responding to oil spill accidents at open sea as well as for the coordination of the overall development of oil response. Previously, the Finnish Environment Institute (SYKE) acted as the main coordinator under the Ministry of the Environment, but since 2019, the Ministry of Interior has been the responsible body in accordance with a new law for rescue operations, which now sets the legal framework for oil spill response (Rescue Act 379/2011).

Under the new Finnish law, the Finnish Border Guard is responsible for responding to oil spills in the open sea, whereas the municipalities (in general, the rescue departments) continue having the responsibility of response on shore and in the archipelago. The expertise of the SYKE and the regional centers for economic development, transport, and the environment (ELY centers) will also remain available in the future, e.g. some of the previous employees of SYKE now work for the Border Guard and the current environmental data of SYKE can be used in case of an accident. Volunteers, such as the World Wildlife Fund (WWF) oil combatting troops, also take active part in response planning, exercises and training.

The coordination of the overall development, i.e. the long-term, strategic planning, includes developing and maintaining the state's ability to respond to oil spills [42]. The planning is based on oil spill scenarios considered as typical or realistic as well as on the calculations of the required response capacity. Typical oil spill scenarios in the GoF are defined as either a grounding of a ship or the collision of two ships [43]. Currently, the response capacity for GoF is defined as being able to recover 30,000 tons in the open sea within 3–10 days [43]. The response focus is on open sea operation with the use of oil combatting vessels: the rapid response in the open sea is considered vital, since the onshore impacts are often more disastrous and the onshore response is slower, in terms of cleaning effectiveness, and more expensive. In accordance with HELCOM recommendations, oil combatting is based on mechanical recovery since the use of dispersants is seen to pose a threat to the sensitive species and habitats in the Baltic Sea (HELCOM Recommendation No. 1/8 [85]). Currently, Finland has 19 oil-combatting boats, operated by the Border Guard, the Finnish Navy, as well as Arctia (a limited company owned by the Finnish state) – most of these are multi-purpose vessels, i.e. used for other purposes as well, but fitted with response equipment. In addition, the regional rescue departments have smaller boats that are used for shoreline response. The communal/ regional rescue departments, SYKE, and the Finnish Navy have also other material and equipment for oil spill combatting, such as booms and skimmers. However, as the changes under the new law are recent, the approach to be implemented by the Border Guard in terms of operational response and response planning is still under development [44].

### 2.3. Knowledge production for oil spill response

Oil spill models are generally used in the Baltic Sea for operational purposes, i.e. in the case of a real accident, as well as for response training and exercises, planning, and determining response capacity (see Table 1 for a summary of the models). The two commonly used models that are applied to predict the fate of oil in the sea are the SeaTrackWeb (STW; [45]) and Spillmod (see, e.g. [46]). These models are both deterministic, in other words, they provide single values (point estimates) without the associated probability distribution (i.e. uncertainties of the knowledge). For example, the potential trajectory of an oil spill provided by the STW is displayed in a map, but the visualization does not include information on the uncertainties and probabilities of the distribution of the oil. STW is an online system developed and updated by the Swedish Meteorological and Hydrological Institute (SMHI). It is the official HELCOM drift model for calculating the fate of oil spill and it is available online for national authorities and certain research organizations. The model uses actual weather data and ocean model (current fields) results to calculate and forecast oil spill drifting.

In the case of an oil spill accident in the Gulf of Finland, the Finnish Meteorological Institute (FMI) has the responsibility to provide oil spill forecasts for authorities. For this, it uses the STW system that can be accessed via a Java client/server application with a GIS-based user-friendly graphical interface. The online available SWT model can also be

**Table 1**
Summary of models for oil spill response in the Gulf of Finland, Baltic Sea.

| | SeaTrackWeb | Spillmod | Bayesian network models |
|---|---|---|---|
| Type of model | Deterministic, i.e. provides point estimates | Deterministic, i.e. provides point estimates | Probabilistic Bayesian network models |
| Input knowledge required/ used | Actual weather data and ocean model (current fields) | Statistical weather and riverine inflow data | Empirical (observational) data, literature, model simulations, and expert opinion |
| Purpose | Calculates and predicts oil spill drifting. Combined with ecological knowledge (BORIS database) | Simulates trajectory of oil | Research models to explore, e.g. response effectiveness and ecological impacts; can be used for decision support |
| Use | For operational purposes, e.g. to predict the oil trajectory in the case of a real accident. Exercises and training; to identify illegal polluters by backtracking. Used by the Finnish Meteorological Institute and response operators | Mainly used for planning of long-term response capacity by the Finnish Environment Institute | Mainly used for academic purposes |

used directly by the response operators themselves. Operators generally access SWT through BORIS 2.0, an online system that offers real time information for response operations and currently includes e.g. information on the location of threatened species on the coast. The BORIS 2.0. system offers information on predicted oil trajectory (SWT data) as well as on the protected areas, aids communication during response, and helps documentation for compensation of damage. SWT/ BORIS 2.0 can also be used for training and capacity planning. Operators often access STW simulations through BORIS during exercises and training, including national (e.g. the Border Guard training together with the regional rescue departments and/or with volunteers), bilateral (with Estonia, Sweden and Russia), and international exercises (e.g. the BALEX Delta under the HELCOM agreement or Arctic water exercise in Oulu under the (Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic (MOSPA) and the Copenhagen agreements). STW can also be used to identify illegal polluters: STW can be combined with HELCOM Automatic Identification Systems (AIS) data to backtrack which ships have passed the track of the oil spill and find possible polluters under the observed wind and current settings.

Unlike STW, SpillMod does not offer real-time information, but generates trajectories using historical meteorological and hydrological data. The user can choose the input parameters oneself, such as, weather, direction of wind or even the assumed effectiveness of the response vessels and equipment (in percentages). SpillMod has mainly been used by SYKE for long-term planning and risk assessments to define the appropriate level of Finnish response capacity, e.g. to demonstrate the scale of accidents and their spatial and temporal dimensions.

In addition, Bayesian networks (BNs, also known as Bayesian belief networks, (e.g. [47]) have increasingly been used by researchers for modelling oil spill risk response in the GoF (see, e.g.[48] for a review on BN models for response): BNs have been applied to predict oil spill occurrence and trajectory [49], but in addition, BNs have recently been utilized to assess the environmental impacts of an oil accident (e.g. [26, 50]), as well as offshore and onshore response effectiveness and cost-efficiency [35,51,52]. Most of the models exclude ice conditions, but Lu et al. [53] have also assessed the effectiveness of mechanical recovery in winter conditions in the Gulf of Finland.

In comparison to deterministic models that do not express the uncertainties related to the system being modelled, BNs [47,54] express uncertainty in the form of conditional probability and depict *subjective* probability. BNs are often displayed as directed acyclic graphs (DAGs) and typically consist of a qualitative and quantitative part [54,55]. The qualitative part describes the modelled system with the use of nodes (uncertain variables) and links (the probabilistic dependencies between the variables). The model can be quantified with the use of conditional probability tables (CPTs). BNs permit quantifying the uncertain dependencies of the modelled system even when data are scarce as they allow integrating different types of knowledge, e.g. empirical data, literature, data simulations, and expert opinion. A BN consisting of random variables can be used to explore the effect of a variable on the other variables in the direction of the links. By adding variables that can be controlled (e.g. managerial decisions that can be implemented) and variables related to utility, loss, or preference, a model can be used to support decision-making. Such influence diagrams have been suggested as useful for decision support as they depict uncertainty and the interactions between system variables, including decisions and outcomes, in a visual and transparent manner [92,48,56–59].

## 3. Theoretical framework and methods

### 3.1. Boundary objects

The role of science and how it can best support policymaking has been subjected to a vast debate: the rather naïve idea that knowledge translates to policy in a simple and linear manner has been widely criticized by, e.g. the notions of Mode 2 knowledge [60,61] and post-normal science [62]. The need for exploring the diversity of ways in which science and policy interact, therefore, remains clear.

In this study, we apply the concept of boundary object to study if and how modelling tools can help to connect science and policymaking. The theoretical concept of boundary object was first introduced by Star and Griesemer [16]. The concept is used to describe hybrid constructs that link elements of different "worlds", such as science and policy, and that integrate multiple types of knowledge and action [15,17,18,63]. In order to do so, boundary objects should be "plastic enough to adapt the local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" ([16], p. 393). This interpretive flexibility means that the objects may have different meanings in different worlds; this allows for negotiation and exchange of knowledge without the need for consensus [64,65].

Common types of boundary objects in environmental governance include, e.g. scenarios, simulation models indicators (e.g. ecological indicators), and tools based on GIS (geographic information systems). Boundary objects are useful tools in environmental governance as they represent a shared meaning that 1) can enhance the credibility, saliency, and legitimacy of knowledge [63], and 2) help representing, learning, and transforming knowledge [15,17]. Boundary objects can also empower participants in problem solving [59] and promote conflict resolutions and collective decision-making ([66]; d'[19,67]).

Model based decision-support tools are increasingly applied in natural resources management and decision-making processes for addressing complex socio-ecological challenges [63,68]. However, not all models are boundary objects per se. For boundary objects to be effective, they must have both the capacity to represent and share multiple types of knowledge from different domains and interests at 'stake' [17,69] as well as generate opportunities to transform knowledge to action [15,63,64,70]. According to Carlile [17,18] boundary objects need to be able to provide different actors with a common syntax for communication (traverse syntactic boundary), translate their knowledge by learning of knowledge differences and dependencies and creating shared meanings (traverse semantic boundary), and transform knowledge to create common interests (traverse pragmatic boundaries).

In other words, including managers/practitioners, policymakers, and other stakeholders (such as non-governmental organizations, businesses, citizens, and local communities) as well as multiple types of knowledge (scientific, expert, local, traditional, and indigenous, etc.) is necessary for models to cross syntactic, semantic, and pragmatic boundaries.

Models can be said to become boundary objects because of their affordances [71], i.e. the possibilities for action [15,19]. The affordances enable or constrain the capacity of models to sustain different interpretations and support learning [19]. Franco [15] suggests that model affordances are necessary to sustain the capacity of boundary objects to both represent knowledge as well as turn knowledge to action. According to Franco [15], the necessary affordances include:

- **tangibility** – the ability to make different types of knowledge *visible* and easily perceived, e.g. making domain-specific knowledge tangible and available for group discussion and negotiation:
- **associability** – the ability of the model to be easily *associable,* e.g. the capacity of the model to relate to its content based on shared attributes, which allows for exploring uncertainties, i.e. identifying knowledge differences and dependencies:
- **mutability** – refers to the *flexibility* of the model and how easy it is to update the model, i.e. the ability to modify the content of the model as new knowledge becomes available:
- **traceability** - the ability of a model to relate its contents temporally and structurally and to allow *for collecting and sharing knowledge-related discussions and negotiations*, and:
- **analysibility** – the ability of turning the model input to *action*, e.g. calculating the impact of different policy choices.

Boundary objects are dynamic [19]. The affordances of boundary objects are shaped by the relational practices and networks through which they are produced and vice versa, i.e. boundary objects influence how science and policy interact. The characteristics of boundary objects are hard to sustain as the problems and people change over time and space [18].

### 3.2. Methods and material

A case study approach was chosen to explore how models work as boundary objects in the context of oil spill risk governance in the GoF, Baltic Sea. The analysis draws on semi-structured interviews as well as on document analysis of government reports and scientific literature. In total, sixteen semi-structured interviews (each between 50 and 120 min) were conducted between the years 2019–2020. The first set of interviews included university researchers who work/ have worked on BN risk models (Helsinki and Aalto Universities or previous university employees, n = 6), the second, practitioners/ administrators (the Finnish Border Guard, SYKE, the Finnish Navy, the Helsinki Rescue Department, WWF Finland, the Finnish Transport and Communications Agency (TRAFICOM), n = 6), and the third, the relevant policy-makers (Finnish Ministry of Environment and Finnish Ministry of Interior, n = 4). The number of professionals working on matters related to oil spill response in Finland is relatively low, which facilitated the identification of interviewees. We used purposeful sampling and snowballing method to identify the best available and information-rich experts. The interviewed practitioners and policy-makers all work in the key organizations involved in oil spill response in Finland and either use the response models or are familiar with the models. The anonymity of the interviewees was guaranteed by means of a coding system: researchers interviewed were annotated as R1- R6, the practitioners as P1-P6, and the policy-makers as D1-D4.

The set of questions reflected the roles and background of the different groups (modelers, practitioners/ administrators, and the policy-makers) and differed slightly depending on the group. The questions for the modelers focused on 1) the models and model construction (e.g. what are the models for, what type of data was used, who was involved in the modelling process, what are the assumptions behind the models), 2) the uncertainties related to the models (e.g how is uncertainty taken into account when models are developed), and 3) the use of models in decision-making context (e.g. how they see the models are currently used, what are the perceived advantages/ limits of the models in terms of the use of models or model results). The questions for the end-users (the practitioners/ administrators and policymakers) focused on the role of science in response planning and operations and more specifically on the scientific models, e.g. what models are currently used and how, if and how uncertainty related to the models is taken into account, as well as the perceived benefits and challenges related to the models used. The interviewees were also asked to identify current knowledge gaps.

The interviews were recorded and transcribed. The data were coded and analyzed with a qualitative data analysis program (Atlas.ti 8). The analytical themes were both deductively and inductively defined. The interview material was first categorized by predetermined codes based on the interview structure and then according to themes that arose from the interviews (based on the frequently occurring themes and words as well as contradictions in the material).

The results (Section 4) provide a synthesis of the interview results and the views of interviewees rather than a full comparison of the views of the different groups interviewed. We have, however, used the coding system to indicate the group where we considered it as relevant and appropriate. The results first assess the use and usability of SeaTrackWeb and SpillMod by examining the different affordances associated with these operational models. The second part analyzes the Bayesian network models and the affordances. We analyzed the current as well as the potential capacity of the affordances associated to the models. The levels (weak, moderate, high) were assigned based on the subjective opinion of the authors and were analyzed by the first author and then verified by the other two authors. We also provide a summary of the main knowledge needs as identified by the researchers, practitioners, and the policymakers.

## 4. Results

### 4.1. The use and usability of the operational models

#### 4.1.1. SeaTrackWeb

Based on our analysis, the SeaTrackWeb model/BORIS system is a **tangible** model in the sense that it makes different types of data and technical information visible and allows for interaction between different response operators (see Table 2 for summary of the affordances associated with the models). In other words, the model utilizes e.g. weather data and ocean models to calculate oil spill drifting in the sea [45]. The results are visualized and displayed as maps with the use of a GIS-based graphical interface, which makes the model results easily understandable. The practitioners noted that the model results aid response operators to e.g. plan where to move units (such as oil booms and combatting vessels) to protect the shorelines most likely to be affected by oil. As noted before (Section 2.3.), the FMI uses STW and is responsible for providing oil spill forecasts for the response authorities in case of an accident. The operators can also interact with the STW model themselves; the online model can be used directly by the operators through the BORIS 2. O online system.

We also suggest that the BORIS system can be considered to have high **analysibility** (the ability of turning the model input to action) as it has been developed by the Finnish Environment Institute in co-operation with a wide range of partners including, e.g. the response operators, FMI, TRAFICOM, SMHI, and EMSA. To ensure it meets the needs of the end users, the partners have been involved in testing the application, e.g. through various workshops and training (P2).

In some sense, the BORIS system also has high **traceability** (the ability of a model to relate its contents temporally and structurally that

**Table 2**
Summary of the models and the associated affordances (both current use and potential capacity). **High capacity** = the capacity allows for the model to be used by practitioners (P) or policy-makers (D) or the model has been developed for specific need/use; **moderate** = the capacity allows for the model to be used to some extent or has some potential to be used by P and D; **low** = the model is not used by P and D and it has low potential to be used by P and D.

| | Seat rackWeb (STW) | SpillMod | Bayesian networks (BNs) |
|---|---|---|---|
| Tangibility (ability to make domain-specific knowledge visible) | Moderate capacity in current use; High potential capacity | Moderate capacity in current use; High potential capacity | Low capacity in current use; High potential capacity |
| Associability (ability that allows for exploring uncertainties) | Low capacity in current use; Moderate potential capacity | Low capacity in current use; Moderate potential capacity | Moderate capacity in current use; High potential capacity |
| Mutability (flexibility of the model) | Low capacity in current use; Moderate potential capacity | Low capacity in current use; Moderate potential capacity | Moderate capacity in current use; High potential capacity |
| Traceability (allows for sharing knowledge-related discussions and negotiations) | Moderate capacity in current use; High potential capacity | Low capacity in current use; Moderate potential capacity | Low capacity in current use; High potential capacity |
| Analysability (ability of turning model input to action) | High capacity in current use; High potential capacity | High capacity in current use; High potential capacity | Low capacity in current use; High potential capacity |

allows for surveying and collecting knowledge-related discussions and connections) as the system also allows for combining ecological data, e.g. data on conservation zones, with oil spill trajectories. According to the practitioners, different administrative bodies have also contributed to the establishment of the BORIS data bases including e.g. ecological data from different research projects, weather information from FMI, and oil trajectories from SeaTrackWeb.

However, the **associability** (the capacity of the STW model/BORIS system to relate to its content based on shared attributes, which allows for exploring uncertainties) remains low. The analysis indicates that STW poorly reflects the uncertainties related to the models as well as the knowledge differences. This also limits the traceability of the model as knowledge related to the uncertainties is not collected for discussions and negotiations. While the STW seems to be able to connect the domains of both research and operational decision-making, their use still has some serious limitations in terms of functioning as boundary objects, such as the failure of the model to "accurately" represent the real-life and their inability to account for different sources of uncertainty and ambiguity (such as multiple knowledge types and the potentially differing perceptions among the various stakeholders concerned) (see Section 3.1). Deterministic models are widely used for planning and training and the practitioners found the models helpful, but in some cases, the model results might end up being "ignored" (P4) as oil combatting is challenging and full of uncertainties. According to the practitioners (P), this was due to multiple factors. For example, as situations change rapidly, the effectiveness of the response equipment can be significantly reduced by number of factors, such as, the location of the oil spill, the oil type, the season, the weather conditions, and technical failures of combatting equipment. Also, as noted by the practitioners, ice cover was also seen to greatly reduce response effectiveness; yet STW or SPILLMOD models are not suitable in ice-covered conditions. The practitioners considered also other sources of uncertainty: they mentioned uncertainties related to the effectiveness of response in terms of new oils (LNG and biofuels) as well as the incertitude related to oil drifting with underwater currents.

The results indicate that the use of models for onshore response was found especially problematic due to a high level of uncertainties. In general, the practitioners saw that models can help in prioritizing and protecting, e.g. certain vulnerable habitats or environment, but that the credibility (and consequently the usability) of models for shoreline operations can be low as explained by one of the interviewees:

> "It (SWT) is good for open sea operations, but the closer you get to the shoreline, the usability becomes crap…(the models) don't work on our shorelines, because it's so scattered. For example, in front of Oulu, there can be 10–20 km wide ocean whirls, which don't move like the model would predict and that can be fatal if you are in an area the size of few square kilometers and the oil does not move according to the model results." (P3).

### 4.1.2. SpillMod

The results suggest that SpillMod is also a visual and **tangible** tool. The results show that the model have also high **analysibility;** when SYKE was the responsible body for cooperating oil spill response in Finland, SpillMod was also used by SYKE for long-term planning and risk assessments to determine the appropriate level of response capacity (Section 2.2). However, the interview results indicate that SpillMod has not been applied by different response practitioners for knowledge sharing, learning, and negotiating, i.e. its **traceability** remains low.

Further, as with STW, **the associability** of SpillMod is limited; as noted by some of the practitioners, the model poorly reflects the key uncertainties related to the planning for the right size of response level (including, e.g. number of boats, size of boats, and location of boats) and the effectiveness of response measures. As noted by one of the practitioners (P3), the response effectiveness of the current measures has been found to be alarmingly low as shown by new research, such as the OPENRISK report [96], where instead of only one model, a combination of four different models was used to calculate the response effectiveness. For example, while the measures may be effective in good weather conditions, accidents occur most likely in bad weather conditions when the response effectiveness can be relatively low [96]. The respondent (P3) also noted that the oil-water emulsification was seen as a major challenge. The volume of emulsified oil can be multiple times larger than the volume of the spilled oil, resulting in "catastrophic amounts" of pollution (P3). As suggested by one of the practitioners: "the assumption that we can deal with 30,000 t in three days, in fact, never holds true…it is impossible to conduct the operations that effectively" (P3). Consequently, one of the practitioners described that Finland's capacity planning based on SpillMod is "theoretical", "simple", and even as "hogwash" (P3). In sum, the results suggest that even with the relatively high level of response capacity that Finland has compared to many other Baltic Sea countries, the response effectiveness is highly uncertain due to various factors.

The ineffectiveness of the response equipment and the large uncertainties are also recognized by the policymakers (D), who highlighted the importance of prevention over response (e.g. AIS, routeing schemes, VTS, and GOFREP). However, the results illustrate that SpillMod (as well as STW) can be seen to have low flexibility and updatability, i.e. **mutability**. Based on the results, we suggest that new information related, e.g. to the uncertainties, has not translated to changes in practices or policy paradigms, but the governance objectives, measures, and methods have become in a way "locked" and the policies remain predetermined. For example, despite the uncertainties related to response effectiveness, the focus under the Border Guard has stayed strongly on mechanical recovery onshore and maintaining a strong response vessel fleet (see also Section 5.1).

## 4.2. The use and usability of Bayesian network models

According to the modellers interviewed (R), the strength of BNs lies in visualizing domain-specific knowledge and addressing uncertainty in an explicit, probabilistic, manner. Thus, their potential for **tangibility** and **associability** can be considered high (see Table 2 for summary of the affordances associated with the models). Indeed, the researchers highlighted that BNs provide new, visual, ways to model complex risks and that they therefore can be useful for practitioners/policymakers: all researchers considered that BNs allow for explicit treatment of uncertainty, which should be an important part of oil spill risk models, as well as risk assessment and management (see also Section 2.3). For example, the researchers highlighted that when assessing ecological risks, further attention needs to be paid on the unevenly distributed risk to coastal and marine species as well as habitat types, and that the accident probabilities and/or transport trajectories are not enough, but models need to also consider the consequences of spills to species and the related uncertainties ([72]; Helle 2015).

BNs are also **mutable**; the researchers noted that the models can be easily updated as new knowledge becomes available. Thus, they can support iterative learning by building on previous models. For example, models for oil spill trajectories can be further developed to study spatial risks [48,73]. Therefore, BNs can support adaptive and iterative management and governance of risks.

Further, the results indicate that the potential for knowledge sharing for discussion and negotiation **(traceability)** is high. While data related to complex risks are often limited, BNs allow for quantifying risk models based on existing data as well as expert knowledge (R1; R2; R4). Indeed, in many of the BN models, the knowledge of end users, i.e. practitioners, was included in the models, and the researchers often saw that the models "depict" the knowledge of the experts (R1; R2). BN models can also support the inclusion of wide range of stakeholders in modelling processes (e.g. [74]) as BN models allow for the utilization of different types of knowledge sources. Similarly, in terms of **analysibility**, many of the interviewed researchers focused on the potential use of BNs for oil spill risk assessment and management, for example, the researchers viewed that the use of influence diagrams including decision and/or utility nodes make BNs suitable for decision-making analysis, e.g. identifying and comparing different decision alternatives and their effectiveness in reaching management objectives (R1; R4) (see also Section 2.3.).

Currently, however, the models have not been able to connect the worlds of science and policymaking and the analysibility of the models in practice, i.e. their use outside of academia, has remained low. The results demonstrate that knowledge generated by BN models has been integrated in the BORIS system. In general, however, when asked about if and how BNs have been used outside academia, the researchers tended to highlight the benefits of the BN models, but were unable to give concrete examples of how the research or the models themselves have actually been utilized. Some researchers noted that even though BNs are not directly used by practitioners, the model results may have had indirect impacts on particular policy outcomes. Yet, only few examples were given, e.g. one researcher assumed that research has played a role in the promotion and adoption of the Enhanced Navigation Support System [95], a system that aims to increase safety of shipping by allowing vessels to send their route plans in advance to marine traffic authorities. The possible influence of BNs on the decision of SYKE not to acquire new response vessels was also discussed by some of the respondents; the researchers focused especially on the paper by Helle et al. [35] that indicated that preventive measures are more cost-efficient than large investments in expensive new vessels. However, there is no evidence that a specific Bayesian model had influenced the decision, and the Border Guard still considers the Finnish response capacity in terms of the combatting vessels as insufficient [42,75].

The results show that the practitioners (P) and policymakers (D) interviewed were largely unaware of the BNs risk models / research. The ones who were familiar with the models were previous project partners with the researchers. The interviewed researchers noted that end users are often only interested in point estimates of uncertainties, i.e. "is it plus or minus" (R4), which makes the use of probability estimates challenging in practice. Also, while much of the research related to BNs was carried in different projects with multiple partners outside the academia, the interaction between e.g. university researchers and SYKE remained low (see Section 5).

In sum, even though BNs have been increasingly applied for the modelling oil spill risks in the GoF, there is a lack of extensive interaction between the researchers and end-users and the research results have not been effectively "picked" up by the potential end users outside academia. Thus, the use of BNs as boundary objects has remained limited.

For example, research on BNs was typically carried under different projects with multiple partners. The project-based research has, however, resulted poorly in knowledge integration between the different partners (R4). The results indicate that the project- based research can be highly fragmented and any meaningful interaction between the project partners remains relatively limited (R4). For example, as the researchers noted, most of their work was carried out under different projects, but the projects usually only last a few years, after which there is no analysis or monitoring on how the actual project results have been utilized.

Also, while projects can involve various partners, in reality, the work may be divided into smaller packages and carried out separately by the partners (R4). For example, one of the researchers noted that while one worked in project involving both the University of Helsinki and SYKE, the research as well as the results presented in the project final seminar were a surprise for the other project partners. The interactions during the project were not continuous but occurred in a haphazard manner (R4). While the researchers acknowledge the need for more interactions, one noted that: "it easily ends up so that the policymakers are in place and the scientists in another and there is no possibility (to interact)" (R4).

Further, the level of understanding of policymaking processes differed among the researchers: as noted above (Section 4.1.) while some researchers had worked together with relevant policymakers, some researchers lacked the understanding of the policy-making process, e.g. they were unable to identify the most relevant end users of their models or the most relevant legislations related to their work:

> "I think there are some gaps – for policy, at least I don't know really, well first you need to define what is policy… we don't know if some accident happens then what is the policymaking procedure or what are the policies, what are the available systems…how do you say, I just feel like there is a gap" (R6).

Additionally, those researchers who have been in closer contact with end users before, felt that they no longer knew the relevant policymakers /practitioners as the Border Guard, not SYKE, is now the responsible authority for oil combatting. For example, one of the researchers noted that:

> "I don't know what the situation is now, we have had nice cooperation with SYKE, but now that the situation has changed under the new law, I don't know who to contact and what is the current approach adopted by the Border Guard" (R1).

While the researchers lacked understanding of the policymaking processes, the practitioners and policymakers had some difficulties to understand the models. In terms of BNs, the practitioners noted a lack of in-depth knowledge about the models and model variables, e.g. why the specific variables were chosen and what the different variables stood for, or how the selected variables were weighted and quantified (P2). For example, referring to one of the example models provided, one of the practitioners commented:

> "For example, here it says "oil type" and what I am interested is what this node includes and how the model deals with it, if we say we have heavy oil or diesel then that affects everything, but how does the

model weight that – will the model say that heavy oil is the worst of all or diesel or where does that come from?" (P2)

One of the interviewed researchers argued that such in-depth knowledge may not be necessary for the practitioners and that the modelers may provide help in the actual use of the models (R1). Still, complex models require a high level of expertise, and our results suggest that they must be used in a co-operative process between the scientists and the end users. Otherwise, they may be too difficult to employ in an operational context of limited time and resources. Models that are "too" complex, therefore, may alienate the different stakeholders from each other rather than bringing them closer together. Usable models would need to be sufficiently complex to represent the system in an adequate manner but still remain accessible to non-expert users [13].

We also identified some future research needs and knowledge gaps based on the interview results (Table 3).

The researchers focused on improving models and highlighted the need for, e.g. integrated models (combining, for example, oil spill trajectory models with the consequences of response effectiveness) as well as spatial and uniform analysis covering the whole of the Baltic Sea as the current work mainly focuses on the Gulf of Finland. Future needs also included further research on the effectiveness and cost-benefit analysis of different response measures and the ecological impacts of potential oil spills. New models especially for iced conditions were called for. In addition, the researchers pointed out the need for research on how to improve expert elicitation (Table 3).

While the practitioners highlighted the need for operational models, the policymakers focused on long-term, strategic decision-making and risk assessment models. However, in general, the practitioners and policymakers identified common knowledge needs, including models for new fuels (such as liquefied natural gas (LNG) and chemicals), models for iced conditions, and models including places of refuge and for post-processing of spilled oil.

## 5. Discussion

### *5.1. How do the different oil spill models work as boundary objects in the science-policy interface?*

We have examined a set of affordances associated with boundary objects that enable collaborative mode of interaction and communication leading to new knowledge, negotiation, and action. The results suggest that the potential of the existing oil spill models to act as boundary objects in the science-policy interface has remained limited as the models lack several of the important affordances. Most importantly, the models have not successfully integrated different types of knowledge (such as scientific knowledge from different domains, multiple types of knowledge, as well as different risk perceptions and values) and have poorly transformed new knowledge to action, i.e. changes in operational practices or policy.

We recognize that the primary aim of the analyzed models has not been to act as boundary objects, i.e. as tools for integrating different types of knowledge and linking knowledge to action. The various model types are created for operational and strategic decision-making purposes. Some, like STW, are aimed for operational decision making after a spill, while many applications of BN have been made for strategic decision making like whether it makes sense to invest on a new oil-combatting vessel, or on better technology to be used to prevent a spill [35]. As such, we suggest that the models are useful and necessary for their own purposes. However, we suggest that the existing models remain calculative rather than transformative, i.e. different types of knowledge and the disagreements or alternative risk framings or solutions are not reflected in the models. As a result, the models support existing, prior specific solutions instead of exploring alternative and innovative ways needed to manage and govern complex risks. Therefore, we suggest focusing on technical models alone is not enough when coping with complex risks and that new types of (participatory) models are needed to complement the existing models (Section 5.2).

The results demonstrate that the currently used oil response models (STW and SpillMod), especially STW, are able to share and visualize different types of *technical* information for discussion and negotiation and turn their input into action. However, only scientific knowledge is included and wider range of stakeholders (such as nongovernmental organizations, citizens, and local communities) has not been engaged in the process of identifying, assessing, and prioritizing oil spill risks. This limits their ability to identify knowledge differences and dependencies (uncertainties) as well as the ability of the models to survey and collect knowledge for discussions and negotiations. In addition, the models lack flexibility and have not supported well the integration of *new* knowledge into operational and decision-making processes. In sum, the models have failed to account for the uncertainty and ambiguity related to oil spill risks. Yet, the practitioners continue to rely upon STW and SpillMod to support response operations as well as risk assessment and management, instead of developing new modelling tools or methods to assess risks.

The study also demonstrates that BNs have high potential to act as boundary objects due to their ability to explore uncertainties as well their flexibility, however, the results of our study suggest that the response operators and policy-makers do not apply BNs and they also remain largely unaware of BN models. In other words, especially the ability of the models to turn their input into action remain low. This may be due to the fact that the funded projects have been focusing on the development of the models, rather than the training of end users. Yet, the researchers were highly optimistic of the potential of the BNs in informing policy-making and some researchers assumed that the model results have already influenced policymaking concerning oil spill policy.

For now, only researchers and response experts have been involved in developing and constructing the BN models. We suggest that combining expert knowledge with data from literature and simulations is useful and necessary for assessing risks and exploring *uncertainties related to modelling procedures* (e.g. its inputs, parameters, and thereby outputs). However, only limited attention has been paid on interdisciplinary research (involving not only natural sciences, but also researchers from the fields of social sciences, law, economics, etc.) and the inclusion of extra-scientific stakeholders (stakeholders from outside the university) and knowledge types significantly limits the traceability and associability of the models, i.e. discussions on knowledge-related

**Table 3**
The main knowledge needs identified by the participants.

| | |
|---|---|
| Researchers | Need for spatial / uniform analysis (covering the whole of Baltic Sea) |
| | Integration of different models (e.g. trajectory and consequences) |
| | Context specific models (increased precision) |
| | Models for protecting species, habitats |
| | Exploring recovery effectiveness |
| | Cost-benefit analysis |
| | Models for iced conditions |
| | How to improve expert elicitation |
| | Risk communication |
| | Interaction between policymakers and practitioners |
| Practitioners | Models for operational purposes |
| | Integration of different models (trajectory and consequences) |
| | Models for iced conditions |
| | Models for new fuels and chemicals |
| | Models for response effectiveness (especially for shore line) |
| | Models including safety ports (places of refuge) and post-processing of spilled oil |
| Policymakers | Models for long-term, strategic decision-making and risk assessment |
| | Models for protecting species, habitats |
| | Models for new fuels and chemicals |
| | Models for response effectiveness |
| | Models for iced conditions |
| | Models including safety ports (places of refugee) and post-processing of spilled oil |
| | Risk communication |
| | Interaction between researchers, policymakers and practitioners |

*uncertainties and ambiguity related to decision-making*, such as risk perceptions and values of individuals.

### *5.2. How do the prevailing science-policy contexts affect the way the models are used?*

Model affordances (or the lack of affordances) may enable and support (or limit) knowledge exchange and shape the way science and policy interact. The results suggest that the affordances of tangibility and analysibility of the operational models have made the models useful for operational and decision making purposes, such as technical risk assessments. However, we suggest that models that support a greater plurality of affordances are needed for governing complex risks, such as oil spill risks. In this section, we discuss the potential of the models to be used as boundary objects in different types of science-policy contexts [6].

Due to their ability to make different types of knowledge visible (tangibility) and to turn the model input into action (analysibility), the operational models have successfully been integrated in the decision-making context. This has implied a **linear knowledge transfer** from knowledge producers to the knowledge users [6]. The affordance of associability, e.g. discussion on uncertainties, does not seem to play a significant role in the use of operational models. The fact that the operational models do not account for uncertainties has not made the models redundant, i.e. they are still utilized by the practitioners. The response operators are aware of the uncertainties, but they complement the model deficiencies by other ways of treating uncertainty, for example, experience and skills of the operators.

Also, as suggested by Franco [15], different affordances are more central than others depending on the type of boundaries. For example, the ability of models to make knowledge visible and to relate their content based on shared attributes may be more important than the other affordances when working at the syntactic (information processing) boundary, i.e. when *transferring* or communicating knowledge and perspectives. In contrast, mutability, traceability, as well as analyzability are in a key role at *translating* knowledge and perspectives across semantic (interpretive) boundaries and *transforming* knowledge across pragmatic (political) boundaries [15]. Our study suggests that the operational models have only been able to transfer knowledge and perspectives. Therefore, we indicate the need for different type of models that also translate and transform the knowledge needed to support social learning among different stakeholders and turn new knowledge into action.

The BNs provide relevant information on uncertainties related to oil spill risks, however, they are not applied by practitioners or the policymakers. On one hand, this may be because the end users perceive the information as inappropriate, in other words, the researchers may be unable to provide end users with relevant and appropriate information (lack of affordances such as tangibility and associability). For example, models that are highly complex and lack transparency, may obstruct the use of information, or even lead to science and policy operating in silos, as “autonomous spheres” [6]. On the other hand, end users may perceive the information as appropriate and relevant, but it is not used due to diverse reasons. The end users may be unable to make use of the results due to missing skills or capacities to use the models or their results, or they may have unreasonable expectations of what science can deliver. There may also be institutional constraints, political stakes and power distributions, and other obstacles that constrain the use of the models or their results [9,76].

In order to bridge the gap between producers and users, the interviewees, in general, focused on measures such as improving the user-friendliness of the models, as well as improving communication and reinforcing interaction between the knowledge producers and users. Second, so far, the communication of research outside academia has remained limited: research results have mainly been communicated in scientific outputs, peer reviewed articles, conferences and project seminars. Consequently, most of the researchers saw the need for new ways to reach policymakers. The practitioners highlighted that research needs to be communicated in simple and clear language and that the knowledge provided needs to be timely and credible. Both researchers and practitioners highlighted the importance of increased interaction: such processes could improve the end users’ understanding of the assumptions behind the models, e.g. why specific nodes were chosen, how the nodes interact, and how the models were parameterized. Further, including experts in defining model structure and in quantifying model could help in testing different scenarios, support learning, strengthen trust, and finally, support the use of models and model results.

While the operational models have influenced policymaking, **policy may have shaped the models and/or the knowledge produced by them** [6]. This seems to hold true, especially when looking at 1) how and which models are used by the practitioners and the policymakers, and 2) how uncertainties are turned “manageable” by reducing and simplifying the scope and complexity of uncertainties. Apparently, end users search for usable and relevant science [9,76] to contribute directly to the design of policy or in the formulation of a solution to a problem. However, as often in the cases of high uncertainty and ambiguity, science can become politicized, and risks are rendered governable by reducing complexity and dismissing, ignoring or even denying uncertainties as well as differing societal values [77,78]: such information is sometimes referred to as “uncomfortable knowledge” [79]. Similarly, in terms of oil spill risks, we suggest that the high level of uncertainties related to defining the “right” level of response capacity has left room for the politicizing of knowledge, i.e. the political use of knowledge that is deemed “fit”. For example, despite the uncertainties related to response effectiveness, the Border Guard still considers the response capacity as insufficient (Section 4.2) and is in the process of purchasing new patrol vessels that will also be used for oil combatting [75]. In Finland, the money used to buy new vessels comes from oil industry (through the Oil Compensation and Supplementary Funds), even though vessels are used for other purposes, as well. Such selective use of knowledge does not support the necessary affordances associated with boundary objects, but in contrast, prevents the integration of new insight as well as the process of iterative learning.

Boundary objects may have limited capacity to bring science and policymaking closer together in situations where these two systems form two distinct **autonomous systems** with their own logic and rules, and where no direct influence exists across the systems [6]. In such cases, also the affordances of boundary objects are non-existent. As mentioned, models constructed in academic “ivory towers” or in short term projects with poor interaction between the project partners, may alienate the different actors from each other rather than provide a platform for collaborative knowledge production. To bridge the gap, Boswell and Smith [6] suggest that further understanding is needed on the political saliency of research, how research is attuned to dominant political framings of policy problems, or to what role science should be given in policy-making.

Finally, we suggest that models have the highest potential to act as boundary objects when **knowledge is co-produced**, i.e. when knowledge is jointly produced in collaborative models of knowledge exchange between researchers and end users [6,80,97]. Indeed, when seeking solutions to complex socio-ecological problems, the shift from the research and use of research results to a new paradigm where the interactive process of knowledge production is increasingly highlighted (e.g. [8,60,62]). Involving stakeholders beyond the academic disciplines and policy making is necessary for producing “socially robust” and context specific knowledge [60,61]. Therefore, we argue that involving stakeholders in model building, e.g. participatory modelling, where stakeholders are involved in some of the modelling phases or throughout the modelling process (from data collection to model construction to the actual use of model) [81,82] can broaden the knowledge base for risk governance and to enhance the usefulness and usability of models in policy-making. This is important in the strategic decision models, which deal with multi-objective problems (e.g. oil spill risk models that include information on the ecological and socio-economic impacts of a potential oil spill) as well as with participatory models that aim to support social learning between various stakeholder groups (see below).

We suggest that in the case of oil spill risks, some examples of co-production exist, e.g. how the BORIS system has been developed in co-operation with different administrative bodies and researchers (see Section 4.1.). We have also identified some examples of knowledge brokers (i.e. individuals that provide a link between knowledge producers and users) and existing boundary objects. For example, we identified some of the study participants as important knowledge brokers that transfer knowledge between the research world and the practitioners as well as between the research world and the responsible institutions such as the Border Guard. Simulations can also act as boundary objects, e.g. the South-Eastern Finland University of Applied Sciences (XAMK) has developed a simulation tool aimed specifically for practitioners that can be used for the training of response operators on land [94].

However, the role of stakeholders other than researchers, practitioners, and policymakers, was not emphasized. We suggest that operational simulation tools can support the ability of the models to make different types of knowledge visible and to explore knowledge related uncertainties, but it is not enough; knowledge production processes need to be fundamentally changed as indicated by the co-production approach. The co-production of knowledge implies a profound paradigm shift to transdisciplinary research. Under co-production, the role of researchers would not only be to provide knowledge for direct decision support (e.g. simulation models aimed at managers), but also help the public to identify and prioritize socio-ecological challenges and help citizens to overcome them (e.g. "eye-opener" models co-constructed by heterogeneous participants that support social learning) (Hare 2008). Such collaborative problem framing and formulation of appropriate solutions may help to discover and tackle the root causes of complex socio-ecological challenges instead of focusing on technological fixes alone.

In sum, the currently existing models have been able to some extent bridge the boundaries between science and policy and between different administrative boundaries, but none of the current models have been able to include a wider range of stakeholders in the modelling process. Further, uncertainty remains unexplored as well as the differing perceptions and understandings of risks. Thereby, the potential of the existing models to support risk communication, social learning, and conflict resolution as boundary objects is significantly limited.

### 5.3. *Future modelling and co-production challenges*

While the future knowledge needs identified by the respondents are important, they mostly focused on improving the technical nature of the models (Table 3). However, the interviewees also saw the need for improving risk communication as well as interaction between scientists, policymakers, and practitioners (Table 3). We suggest that future research on models as boundary objects could provide insight into how models can bridge the knowledge gaps between the knowledge producers and the users. Models as boundary objects can also help us understand how different societal stakeholders identify, perceive and value oil spill risks in the GoF. Without this information, it remains difficult to enact changes towards more sustainable societies.

It must also be noted that participatory forms of governing have a number of challenges, and therefore it is important to carefully assess whether, and under what conditions, co-production is desirable and needed [98]. Considerations over power relations in the processes is especially highlighted: power relations shape the affordances of models [19]. Without consideration over power, participation might merely refer to a random process of selecting participants that fails to pay attention to the underlying political and economic mechanisms that are ultimately behind many of the global environmental problems [83].

Finally, the models alone are not enough, but co-production needs to be supported by the institutionalization of structures, rules, processes and practices that ensure that evidence to inform policy-making is in a transparent manner through deliberative processes [93]. A detailed discussion on ways to institutionalize the change towards co-production is out of the scope of this paper. However, we suggest that the Border Guard, the responsible body for oil spill response operations and planning in Finland, needs to consider new ways to help to integrate scientific knowledge into policymaking processes as well as recognize and support the use of different types of knowledge, i.e. local knowledge and values, in risk assessments and management. As shown, so far, the Border Guard largely relies on technical tools, such as deterministic models and conventional risk assessments as well as the investments in expensive response vessels, but the approach, which might not be sufficient 1) when uncertainties related to oil spill risks are taken into consideration, and 2) in the face of surprises/ unexpected event. In sum, we suggest that the Finnish Border Guard needs to take concrete steps to promote adaptive and robust decision-making, i.e. provide space for discussions between different fields of research as well as extra-scientific stakeholders.

## 6. Conclusion

Scientific knowledge, such as models, provides important input to the governance of complex socio-ecological risks, such as oil spill risks. In this study, we conceptualized oil spill risk models as boundary objects to explore the potential of the existing models to integrate different types of knowledge systems and values in risk governance and bridge the gap between science, practice, and policy. We analysed the model affordances that enable models to act as boundary objects as well as how different science-policy contexts may support effective knowledge exchange.

In general, it seems that the existing models remain limited in their capacity to act as boundary objects. While the operational, deterministic, models are largely employed by the practitioners for different purposes, they poorly reflect the uncertainties related to the risks. The BN models treat uncertainty explicitly, but their use outside of academia has remained low. Furthermore, the models are based on scientific data, whereas extra-scientific stakeholders remain largely excluded in the modelling process; different types of knowledge and the alternative risk framings or solutions are not reflected in the models. In sum, while it seems that in some cases the models have been able to translate knowledge and perspectives across the syntactic boundary, they have failed to translate and transform knowledge across the semantic and pragmatic boundaries. However, traversing these latter boundaries is needed to support social learning among different stakeholders and turn new knowledge into action. We argue that the operational models are fit for operational and strategic decision-making purposes (i.e. operational decision making after a spill or preventive and other actions before a spill), but remain instrumental. As such, they may hinder effective knowledge exchange and even block learning between different stakeholders in governance processes. Finally, we suggest that involving a wide range of stakeholders in the modelling process could facilitate the exploration of new, alternative ways to manage and govern complex risks and to inform transformation both in policy and practice.

## CRediT authorship contribution statement

The study was designed jointly by Tuuli Parviainen, Päivi Haapasaari, and Sakari Kuikka. Tuuli Parviainen had the main responsibility in conducting the interviews, the analysis, and the writing of the paper. PH and SK provided comments and took part in review and editing of the paper. SK was responsible for the funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104863.

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